S14 - Additive Manufactoring

Keynotes

S14-283

Production of spherical micron-sized polymer particles for Additive Manufacturing by liquid phase processes

*Dechet, Maximilian A.; Kloos, Stephanie; Peukert, Wolfgang; Schmidt, Jochen**

Abstract

Selective laser sintering (SLS) is an additive manufacturing process that yields excellent part qualities with good mechanical properties. This process employs micron-sized polymer particles, which are selectively fused by a laser. While there seem to be hardly any boundaries regarding design, there are quite some restrictions concerning the variety of commercially available SLS materials. At the moment, the most widely used polymeric material for SLS is polyamide 12 (PA12), with a market share of roughly 95%. In order to broaden the field of application of SLS, novel polymer powders with good handling properties are needed. The polymer particles need to be optimized regarding size, shape, flowability and packing characteristics. In this contribution novel melt emulsification [1] and precipitation processes are discussed. Bulk polymer materials are directly converted to spherical micron sized particles in a single unit operation. The produced particles are characterized regarding their size and morphology via electron and light microscopy. Furthermore, also crystallinity, structural characteristics and flowability are analyzed and the product properties are correlated with process parameters. This way, we show the potential of these processes for the production of novel easy-to-handle polymer particles for SLS.

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S14-455

Understanding the Temperature Field in Fused Filament Fabrication for Enhanced Mechanical Part Performance

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Abstract

The Fused Filament Fabrication process is the most widely used process for prototyping. The use of variable feedstock material, specimen geometries, pre-processing software, and printers makes comparability and reproducibility challenging, because the part properties not only change with varying print parameters, but also with changes in the slicing routine and tool path generation. The sequential part build-up causes a transient temperature field that affects the local microstructure and interfacial bonding and thus the macroscopic properties. The weld line formation between neighboring beads within layers as well as between layers has been identified as one of the biggest factors affecting mechanical properties. To circumvent these constraints and study the temperature field, a custom python™ program was developed and programed, which allows control over traditional user adjustable print parameters, such as print speed, but also infill angle, custom infill patterns, distance between beads, and amount of material extruded along a bead. Using this tool path generation tool the cooling and re-heating effect during printing was studied using an IR thermal camera and additional thermocouples on the build platform. Varying the nozzle temperature, print speed, layer height and material properties, it was shown that all paremeters have all significant effect on the cooling of the newly deposited layer and the re-heating of previously deposited layers. The re-heating of the layers above the glass transition temperature can be correlated to the resulting weld strength in the printed specimens. A numerical analysis in ANSYS Mechanical using the element death and birth effect proved that radiation should be included because of the initially high deposition temperatures, and that the presence and size of voids affect the re-heating or cooling rate during the deposition process.

S14 - Additive Manufactoring

Oral Presentations

S14-78

Flow Behaviour of Laser Sintering Powders at Elevated Temperatures

Van den Eynde, Michael; Van Puyvelde, Peter*

Abstract

Powder flowability is a determining factor in many industrial processes. In laser sintering (LS), for example, a well-flowing powder is required to enable the deposition of smooth layers with a thickness of only 100 μm[1]. Characterising what powders meet these flow requirements is, however, not straightforward. Most industrially used characterisation techniques are indexers, which means their results cannot just be extrapolated to any flow field. This research evaluates the flowability of multiple powders intended for laser sintering. A dynamic angle of repose (dAoR) and Hausner ratio (HR) are used to provide a quick first screening. Powders passing these first tests are then subjected to a spreading experiment, which evaluates layer quality and density. The layer density is directly relevant for the sintering process, as denser powder layers yield mechanically stronger products[2]. Results show that the dAoR is able to provide a quick screening of some powders. However, powders scoring the best in the dAoR are not always the optimal powders for LS. Moreover, flowability at ambient conditions is not a sufficient criterion for LS powders, as the entire process occurs well above room temperature. Powder rheometry, in combination with DSC measurements, is therefore used to assess a maximum bed temperature at which the powder is still spreadable. The spreading experiment is also expanded to incorporate powder heating, mimicking LS even further. Finally, also humidity is taken into account. The moisture content and uptake rate are examined via thermogravimetric analysis. Results on the standard PA12 2200 show that small amounts of moisture decrease the flowability, compared to the dried powder. Moisture content should thus thoroughly be monitored in lab conditions, to provide directly relevant insights for the laser sintering process.

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S14-138

Temperature Induced Ageing of PA12 Powder During Selective Laser Sintering Process

Benz, Johannes; Bonten, Christian*

Abstract

The selective laser sintering process has the potential to permanently overcome the boundary between model construction and functional components. The basic prerequisite for this is that components with reproducible quality can be manufactured. For this purpose, the virgin material must already be of the same quality. During the process, the laser sintered powder is heated to temperatures just below the melting temperature and held until the end of the building process. This results in thermal aging of the powder. Powder, which is not sintered, gets refreshed after the production process with new powder and can be reused. Due to the repeated refreshing pro-cess of the aged powder, a mixture is produced whose quality is difficult to define. By means of rheometry and differential scanning calorimetry (DSC), both new powder and powder, which was taken from a laser sintering process, are characterized. At the same time, the thermal aging is simulated by means of an oven heat. The rheo-logical investigations show that the storage results in an increase of the viscosity, both in the process and in the oven. The reason is a postcondensation and thus the extension of the molecular chains. In addition, extended molecular chains lead to a faster reaching of the sol-gel transition and thus to a change from viscous to elastic material behavior. The postcondensation also leads to an increase in the melting temperature, which can be de-tected by means of DSC. The aging of the laser sinter powder can be reproduced by means of the oven storage and permits further investigations to ensure the quality of the virgin material.

S14-172

Control of Fused Deposition Modeling Melt Extrusion and Laydown

Hebda, Michael James; Caton-Rose, Philip; Whiteside, Ben; Coates, Philip*

Abstract

Melt extrusion and laydown of polymer within the FDM process is common practice but little is understood about laydown of polymer in relation to melt flow and die swell. This paper takes a standard 0.4 mm FDM nozzle and stepper motor controlled extruder setup and studies the laydown and extrusion techniques associated with FDM through high-speed camera work (Fig 1) and advanced data analysis techniques. Custom software has been created in order to measure and control extrusion speed, pressure and temperature with a view to linking laydown width and depth during single path extrusion to process settings. Higher rates of polymer extrusion speeds (335 mm/min) increased (Fig 2) die swell which must be considered in order to control path width during the manufacturing process preventing manufacturing issues such as negative gap width and model overfill.

S14-194

Welding of 3D Printed Carbon Nanotube-Polymer Composites by Locally Induced Microwave Heating

*Sweeney, Charles; Saed, Mohammad; Green, Micah**

Abstract

Additive manufacturing through material extrusion (ME), often termed 3D printing, is a burgeoning method for manufacturing thermoplastic components. However, a key obstacle facing 3D-printed plastic parts in engineering applications is the weak weld between successive filament traces, which often leads to delamination and mechanical failure. This is the chief obstacle to the use of thermoplastic additive manufacturing.(1) Here we report a novel concept for welding 3D-printed thermoplastic interfaces using intense localized heating of carbon nanotubes (CNTs) by microwave irradiation. The microwave heating of the CNT-polymer composites are a function of CNT percolation, as shown through in situ infrared imaging and simulation. We apply CNT-loaded coatings to 3D printer filament; after printing, microwave irradiation is shown to improve the weld fracture strength by 275%. These remarkable results open up entirely new design spaces for additive manufacturing and also yield new insight into the coupling between dielectric properties and RF field response for nanomaterial networks.

S14-241

Processability of Perlite-Filled Polypropylene Composites in Extrusion-Based Additive Manufacturing

Schuschnigg, Stephan; Spörk, Martin; Sapkota, Janak; Weingrill, Georg; Fischinger, Thomas; Arbeiter, Florian; Holzer, Clemens*

Abstract

Extrusion-based additive manufacturing, also known as fused filament fabrication, is a versatile and popular additive manufacturing technology, which relies on the extrusion of thermoplastic filaments to produce a three-dimensional object in a layer-by-layer technique. So far only a limited number of commercial materials are available for this technology. Especially technologically relevant semi-crystalline polymers lack studies devoted to extrusion-based additive manufacturing. This work aims at extending the material database for extrusion-based additive manufacturing to polypropylene. In order to overcome the critical shrinkage and warpage issues of polyolefins, polypropylene was filled with the spherical filler expanded-perlite, a volcanic silicate found freely in nature. The impact of filler size and content as well as the addition of an amorphous polymer was studied for specific properties that are most relevant in connection with 3D-printing. A detailed analysis on the material's shrinkage, mechanical, thermal and morphological properties was performed. Moreover, both the processability and the printability of the filaments were studied by means of industrial-scale extrusion and the printing of specific test specimens explicitly prone to warpage. In summary, a polypropylene compound containing small-sized expanded-perlite and amorphous polyolefins led to a well printable product that distinctly improved the warpage, shrinkage and mechanical properties. Thereby, our findings prove the successful application of semi-crystalline materials for extrusion-based additive manufacturing under appropriate conditions.

S14-244

Effects and optimization of processing parameters in fabrication of polyphenylsulfone microspheres via spray drying

Mys, Nicolas; Verberckmoes, An; Cardon, Ludwig*

Abstract

This article describes the processing of polyphenylsulfone (PPSU) into microspheres via the physicochemical method called spray drying. These microspheres have the potential to be used as build material for selective laser sintering provided they have spherical morphology and have a mean particle size in the range of 45-95 micrometer. The effects of the different processing parameters on these two response factors have been investigated in spray drying of PPSU by Design of Experiment. A plot is predicted in which size and morphology are optimized and combined in order to find the ideal parameter set for production. The effect of polymer concentration, solution feed rate, atomization flow rate, inlet temperature and polymer grade was optimized using a five-factor and two-level factorial design with center points. Experimental validation is performed to certify the conclusion. The particles were characterized by SEM, DSC and GPC. Particles showed no significant degradation due to processing and had overall good morphology.

S14-264

A novel process for tailored stiffness and strength in extrusion based additive manufacturing

Van De Steene, Willem

Abstract

Extrusion based additive manufacturing (AM) techniques have gained interest and were continuously developed during the last quarter-century. However, the currently integrated processes have their limitations in different aspects. When compared to injection moulded parts, additively produced parts often suffer from limited mechanical properties, uncontrollable anisotropy, higher surface roughness, the need for support structures during production, limited process speed, etc. In this research, a novel (AM) process to reduce the aforementioned limitations is proposed. Therefore, an additive manufacturing platform with two additional degrees of freedom compared to conventional AM machines and with custom-made software was developed. This system enables Curved Layer Additive Manufacturing (CLAM). This process allows for the development of innovative build schemes, which result in a severe reduction of required support material. Another advantage of this extra flexibility is the possibility to tailor the part’s strength and stiffness according to the loads it will be subjected to. This characteristic is promising since the machine is able to process both thermoplastic and continuous fibre reinforced thermoplastics. Such an engineering solution allows for weight reduction and reduced material consumption. Furthermore, the manufactured part‘s surface roughness can be reduced by adding a finishing layer. Finally, this technology allows automated filament placement on curved layers, non-geodesic filament winding of complex shapes, the creation of continuous fibre reinforced metamaterials, etc. This study compares and assesses build time, surface roughness, mechanical properties such as flexural strength and modulus, impact strength, etc. of samples produced with both regular extrusion based AM and with the own CLAM technique.

S14-286

Fatigue crack growth propagation in 3D-printed polymer structures – a comparison of different additive manufacturing technologies

Knöchel, Johannes Friedrich; Kropka, Micheal; Neumeyer, Thomas; Altstädt, Volker*

Abstract

Additive manufacturing technologies enable the production of plastic components with complex geometries that cannot be realized by conventional mold-based methods in small production lots. The combination of design freedom with sufficient mechanical properties enables the cost-efficient production of functional prototypes. In order to elevate 3D printing from a "rapid prototyping" to a "rapid manufacturing" technique for serial products, the fatigue behavior of 3D-printed parts has to be deeply understood. Hence, the aim of this study is to analyze the fatigue properties of 3D-printed ABS parts to evaluate the lifespan in daily use in comparison to injection molded (IM) parts. For this purpose compact tension (CT) samples, manufactured by Fused Filament Fabrication (FFF) and Arburg Plastic Freeforming (APF), were analyzed under dynamic mechanical load and compared to IM samples by investigating the fatigue crack propagation (FCP) behavior. Using microscopic analysis of the fracture surface, characteristic regions of the crack path are investigated in detail in order to identify predominant crack mechanisms. It can be concluded that the crack propagation rate is quite similar for FFF and IM specimens. The stress intensity factor at which the crack growth is initiated (Kth) is on the same level as for IM samples. These findings are proven by the corresponding fracture surfaces, which reveal a homogenous material structure in both cases. APF samples show a slightly slower crack propagation speed compared to IM and FDM samples. Analysis of fracture surfaces indicates, that the lower propagation rate is induced by a high porosity of more than 5 %, which causes multiple crack branching. The evaluation of the FCP behavior in 3D-printed polymer structures reveals the potential of 3D printing with regards to its development from a "rapid prototyping" to a "rapid manufacturing" technique for technical products.

S14-288

Structure-property relationship of additive manufactured thermoplastic polymers processed with Arburg Freeformer

Kaut, Franziska; Cepus, Valentin; Grellmann, Wolfgang*

Abstract

The most additive manufacturing technologies share the similarity in production of parts layer by layer on the basis of physical models created with three-dimensional computer aided design (CAD) models. In contrast to the longer on market available additive manufacturing methods, the principle of Arburg Freeformer base on melting of conventional plastic granules with an injection molding plasticizing unit as base material. A stationary discharge unit with an integrated nozzle- valve system applies thin plastic droplets layer by layer onto a component carrier using high frequency piezo technology to open and close a nozzle-valve system at a specified cycle of 60Hz to 200Hz. Compared to fused filament fabrication (FFF), which is the most common process in additive manufacturing with material extrusion, the Arburg Freeform System (AFS) has a higher degree of freedom in material variation. In this work, structural properties are correlated with the mechanical and physical properties of additive manufactured thermoplastic polymers. Focused are investigations of interlayer adhesion of layerwised build specimen and parts.

S14-365

Fused Deposition Modeling of Poly(vinyl alcohol) Based Filaments

Chen, Gang; Chen, Ning; Wang, Qi*

Abstract

Fused deposition modeling (FDM) is one of the most widely used 3D printing technologies. However, the commercially available filaments for FDM are ABS, PLA, etc., which are much higher price and lacking functionality. Therefore, preparation of new filaments suitable for FDM is promising but undoubtedly challenging. Poly(vinyl alcohol)(PVA) with excellent comprehensive properties is a good biodegradable material for FDM. The key is to realize the thermal processing of PVA. In this paper, based on our former research work, the hydroxyl ionic liquid (IL) was used to control the supramolecular structure of PVA. The melting point of PVA gradually decreases from 217.3 to 146.3 along with the glass transition temperature promptly decreases from 76.61 to 11.39 upon the addition of IL, revealing that IL could act as an ideal plasticizer for PVA. The Flory-Huggins interaction parameter of PVA/IL system is at 160oC, which suggested that the binary blends of PVA/IL system was fully miscible in the molten state. The O-H stretching bands shifts to a higher wavenumber about 19cm-1 together with the striking change of peak shape in amorphous region in FT-IR, which guaranteed the interaction between IL and the hydroxyl groups of PVA. This interaction also improved the thermal stability of the PVA/IL system during processing. Then a new kind of PVA-based filament with good flowability and toughness suitable for FDM is prepared via this simple and facile strategy. The obtained PVA/IL filament exhibit excellent ionic conductivity up to 2.82×10-3S/cm with 35wt% content of IL. Furthermore, the effects of the parameters such as the layer thickness, air gap, as well as filling angle on the structure and properties of PVA/IL parts fabricated by FDM were discussed.Finally, the human jaw model and the biological scaffold with complex structure and good compressive modulus were fabricated.

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S14-430

Polyetheretherketone hybrid nanocomposite filaments for 3D printing

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Abstract

3D printing is currently recognized as a disruptive polymer processing technology. However, although recent research efforts have focused on the identification of the materials requirements for successful printing (physical, chemical, thermal and rheological properties), the commercial range of polymer filaments continues to be surprisingly limited. This is particularly noticeable when the aim is to add functionality to printed parts, such as thermal or electrical conductivity. Electrically conductive composites are attractive for several applications depending on their conductivity range. Examples are electrostatic dissipation (10-8 – 10-6 S.cm-1), electrostatic painting (10-6 – 10-4 S.cm-1), electromagnetic interference (EMI) shielding (10-3 – 10-1 S.cm-1) and lightning strike protection (>101 S.cm-1) applications1. Polymers with aromatic carbon backbone characteristically present excellent mechanical properties, high thermal resistance and may establish strong interactions with graphene-like surfaces via π-π stacking2. The present work reports the preparation of an electrically conductive thermoplastic composite by melt mixing using polyetheretherketone (PEEK), graphite nanoplates (GnP) and carbon nanotubes (CNT), its subsequent processing into conductive filaments and a few preliminary printing experiments. Characterization encompasses electrical conductivity, tensile strength and morphology.

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S14-457

A new approach for getting more homogeneous Temperature Fields in Selective Laser Sintering

Greiner, Sandra; Lanzl, Lydia; Zhao, Meng; Wudy, Kathrin; Drummer, Dietmar*

Abstract

During the last 10 years, selective laser sintering of polymers (SLS), one of the most promising additive manufacturing technologies, strongly developed from rapid prototyping towards rapid manufacturing. However, two main drawbacks have to be overcome, the limited range of processible materials and the lack of reproducibility of geometrical and mechanical properties in dependence on part positioning and processing parameters. The precise configuration of a homogeneous temperature field might be one of the most crucial factors for stable and reproducible processing, especially when new materials are to be tested. To date, commercially available machines work with built chamber temperature gradients of 7 to 10 K, ignoring the thermal influence of exposure. Within this work, to date available systems for temperature measurements will be evaluated in terms of applicability in a powder based process. In addition, a new method for calibrating the temperature field of a SLS machine with an eight zone heating system will be shown and discussed. Finally, the resulting temperature field is applied to the powder based process and verified by thermogravimetric analysis.

S14-458

Developing a patient individualized flexible silicone implant using SLS and vacuum die casting

Drummer, Dietmar; Launhardt, Martin; Ebel, Nina; Weyand, Michael; Volk, Tillmann; Kondruweit, Markus*

Abstract

The Selective Laser sintering process (SLS) allows the manufacturing of complex thermoplastic parts without the need for an expensive mold. However, the available material portfolio is very narrow and yet does not offer a silicone rubber type material, which can be used for medical applications. Thus, in this approach the applicability of SLS vacuum die casts for the manufacturing of patient individualized flexible silicone implants shall be analyzed. The heart insufficiency is medically a complex desease, which usually requires eventually heart transplantation surgery. However, an internal flexible heart supporting system could support and cure the organ significantly. This requires patient individualized geometries, flexible structures and reinforcements such that compression forces only affect the heart but not the surrounding organs. Therefore, basic studies on the molding and demolding of silicon specimens using SLS vacuum die casts shall be investigated as well as the possibility for including flexible reinforcement structures. First, simplified mechanical tests show the feasibility of the manufacturing process as well as optimization potential using patient individualized geometries. First functional silicon heart supporting structures are successfully manufactured and can be used for medical tests.

S14 - Additive Manufactoring

Posters

S14-50

Comparison of the mechanical properties of 3D printed polymers and TiAL6V4 used in medical applications

Weißmann, Volker

Abstract

Additive manufacturing technologies such as 3D printing have enabled the production of complex structures and parts which find widespread use in engineering applications. Medical engineering with its need for materials with exceptional properties has taken on a key role. In addition to chemical resistance and biomedical tolerability (sterilization resistant, non-toxic and non-sensitizing), the suitability of these materials depends in particular on their mechanical properties. Biomedical applications such as, for example, bone substitutes often require mechanically optimized structures whose properties are determined not only by manufacturing conditions but also by the sizes and forms of the structures as well as the materials used. The priority of objectives in structure development include besides a reduction of implant stiffness, the achievement of bone-like mechanical characteristics and the realization of the substitute structure in a porous (micro, macro) structure or surface. While several medical technical problems with a requirement for defined mechanical properties have drawn upon titanium alloy-based applications, the use of polymers has just begun. The present paper compares the mechanical properties of 3D printed, load carrying structural elements (scaffolds) made of TiAl6V4 powder that are suited for use as bone substitute and scaffolds made of polymer materials (PEEK, ABS). Characterization was performed by assessing the functional relationship between the experimentally determined porosity and the modulus of elasticity. Special emphasis has been placed on their specific flexibility as the determining factor for deformation resistance. It offers an excellent possibility to establish a direct relationship between porosity and elastic modulus. Besides the material characteristics of the materials themselves, scaffolds with different porosities have been assessed and compared directly with the characteristics of the human bone (cortex, cancellous bone).

S14-333

Development of novel Nanocarbon composites based on functionalised MWCNTs and Poly Lactic Acid for Fused Deposition Modeling applications

Cano, Manuela; Parra, Julián; Ramirez, Maria Dolores; Morales, Gabriel; Malik, Sharali*

Abstract

Additive manufacturing is an emerging technology which could potentially initialise another industrial revolution. Important advances in the optimization of the 3D printers have been carried out in the last 10 years(1). One of the most promising techniques for rapid design and prototyping is Fused Modeling Deposition (FDM) due to the facility to extrude thermoplastic polymers in the form of filaments2. The 3D market demands a wide range of polymer materials to be printed in different applications such as automotive, aeronautics, food packaging and consumer goods1 etc. Thermoplastics reinforced with carbon nanomaterials shows an interest for the automotive or aeronautic sectors due to high mechanical, thermal and electrical properties(2). One of the main goals focuses on the optimization of the industrial processing of these polymers composites and their adaptation to the 3D specification printing. In this work we present a straightforward non-wet route to fabricate PLA/MWCNTs composites filaments by small-scale industrial extrusion process to be used in 3D printers and the studies of mechanical properties of the developed filaments. MWCNTs were first functionalised following the procedure described(3) to produce the composite with the aim to increase the nanomaterials dispersion in the polymer matrix. Pre-dispersion of MWCNTs in PLA was carried out by using a mechanical milling process. Subsequently the pre-dispersion was extruded into a filament of 1.75 mm mean diameter. Preliminary results show an enhancement of tensile load (8-10%) on filaments reinforced with non-functionalised MWCNTs and even more (16-18%) when these filaments are made of functionalised MWCNTs.

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S14-401

Determination of the Short Time Stability of Polymers

Schawe, Juergen E.K.

Abstract

The thermal short time stability is relevant for fast heating processing techniques like fused filament fabrication, selective laser sintering or polymer welding. Also the application of polymeric materials with temporary stress at high temperatures requires knowledge of the short term stability at high temperatures. Thermogravimetric analysis (TGA) is a standard technique to measure the thermal stability. This technique has two drawbacks: • The decomposition at high temperatures does not necessarily contain the same reaction steps as measured by TGA. • TGA is not sensitive for degradation steps which are not related to mass loss. However, such reactions can significantly influence the properties of polymeric materials. It is shown on differently stressed polymers that the crystallization behavior changes sensitively with molecular modifications due to the stresses. The modification in the crystallization behavior due to thermal stress can be studied by fast scanning calorimetry (FSC). The change of the crystallization kinetics due to thermal stress is analyzed. From the measured curve a stability parameter can be derived which characterized the thermal degradation. The stability of polyamides and polymer materials developed for selective laser sintering (SLS)is analyzed for fast heating processes. The results show a remarkable discrepancy to the TGA results and the high sensitivity of the change of the crystallization behavior for the early steps of decomposition reaction.